

AARTFAAC: Towards a 24x7, All-sky Monitor for LOFAR

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The AARTFAAC project aims to implement an All-Sky Monitor (ASM), using the Low Frequency Array (LOFAR) telescope. It will enable real-time, 24x7 monitoring for low frequency radio transients over most of the sky locally visible to the LOFAR at timescales ranging from milliseconds to several days, and rapid triggering of follow-up observations with the full LOFAR on detection of potential transient candidates. These requirements pose several implementation challenges: imaging of an all-sky field of view, low latencies of processing, continuous availability and autonomous operation of the ASM. The first of these has already resulted in the correlator for the ASM being the largest in the world in terms of its number of input channels. It will generate $\sim 1.5 \cdot 10^5$ correlations per second per spectral channel when built. Test observations using existing LOFAR infrastructure were carried out to quantify and constrain crucial instrumental design criteria for the ASM. In this paper, we present an overview of the AARTFAAC data processing pipeline and illustrate some of the aforementioned challenges by showing all-sky images obtained from one of the test observations. These results provide quantitative estimates of the capabilities of the instrument.

Key words: Calibration, Imaging, Aperture Array, Radio Sky Monitor, Radio Transients.

1. Introduction

The recent serendipitous discoveries of several astrophysical radio transients at a variety of flux and time scales (see e.g. [1]) has opened up a new window in the search for exotic objects of both known and unknown type. It is felt that the transient or dynamic radio sky, specially at low frequencies, should be rich enough to benefit from blind surveys along the lines of wide field instruments at higher energies (X and γ rays), which have been very successful at detecting transient sources. Further, it is argued that for the problem of transient detection, one is better off having a much larger field of view, while trading off sensitivity [1].

It is in this context that the Amsterdam-ASTRON Radio Transient Facility And Analysis Center (AARTFAAC), a collaboration between ASTRON and the University of Amsterdam, aims to implement a near real-time, 24x7 All-Sky Monitor (ASM) for the LOFAR. Such an instrument will enable monitoring for low frequency radio transients over most of the sky locally visible to the LOFAR at timescales ranging from seconds to several days. In the following sections, we introduce the ASM in more detail and present some initial results.

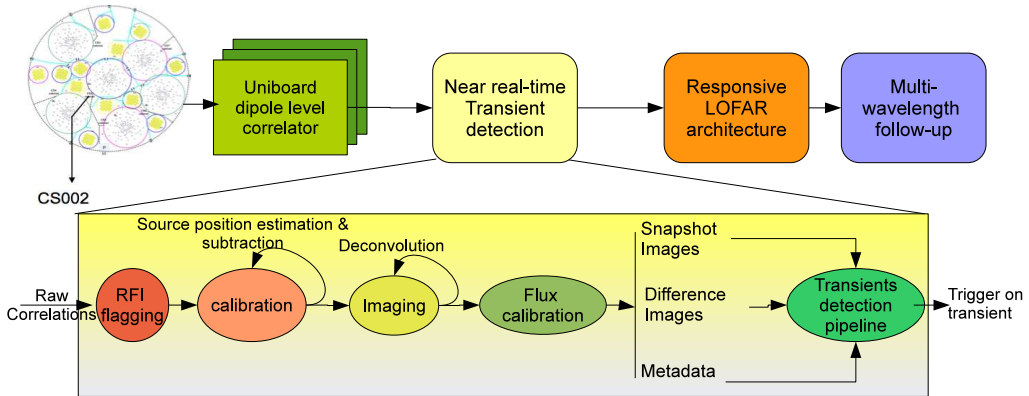


Figure 1. The main components of the AARTFAAC ASM.

2. The AARTFAAC ASM

LOFAR [2] is an array of ‘stations’ spread over hundreds of kilometers, while each station is itself an array composed of two kinds of receiving elements: dipoles or Low Band Antennas (LBA) operating between 10 – 80 MHz, and tiles or High Band Antennas (HBA), operating between 110 – 240 MHz. The ASM will use six stations at the heart of LOFAR and will be a zenith-pointing, transit mode instrument. This configuration makes the ASM a 288-element array, spread over ~ 350 m providing almost full UV coverage and a well defined PSF which does not change with time. Usually, the digitized outputs of every element in a station are coherently summed to form a beam in a given direction before being available for correlation. This, however, restricts the field of view of a station to a few degrees. The ASM needs to correlate the signals from all signal paths to image the full field of view (2π sr (all-sky) for LBA and $\sim 1.5 - 10\%$ of the sky for the HBA, depending on the observing frequency). For continuous monitoring, the ASM operates in a piggyback fashion simultaneously with regularly scheduled LOFAR observations, thus sharing their observational parameters. The overall control flow and main components of the ASM are depicted in Fig. 1, and are further described below.

The AARTFAAC correlator will have 576 inputs (dual polarization from 288 elements) leading to $\sim 1.5 \cdot 10^5$ correlations for each spectral channel. Its implementation scheme is described in [3]. The current hardware specifications assume 24 kHz spectral and 1 second temporal resolution (to prevent time and bandwidth smearing). This results in a sensitivity of ~ 4 Jy at 60 MHz. The resolution of 0.8 square degrees leads to a confusion noise of ~ 8 Jy at 60 MHz, leading to the expectation of the ASM being confusion noise, rather than thermal noise limited. The total available bandwidth is ~ 13 MHz, which can be arbitrarily distributed over the 100 MHz total available digitized band. Thus, the ASM has a very versatile instantaneous spectral coverage over two octaves in the LBA, and one octave in HBA.

The correlator outputs are first passed through an RFI excision stage, the challenge being to generate appropriate RFI masking with the limited temporal

and spectral baseline available due to the near real-time nature of the system. The correlations are then calibrated and imaged with low latency. This stage may require multiple iterations and dominates the computing. The output images will then be flux calibrated, forming the input to the Transients Pipeline [4]. This carries out source extraction, source association, and the generation of light curves from existing observations for transient detection. It will also generate low-latency triggers to a LOFAR architectural module termed the ‘Responsive LOFAR module’, which can trigger multi-wavelength follow-up observations with a variety of instruments.

3. ASM Calibration Challenges

ASM calibration refers to the estimation of a complex direction independent gain per antenna and direction dependent parameters per calibration source, characterizing the ASM and propagation through the ionosphere. Traditionally, calibration is carried out periodically, with the expectation that instrumental and observational parameters remain stable in the interim. However, the ionosphere can have a significant effect on the propagation of low frequency radio waves as observed by the ASM. Thus, the ASM requires continuous, direction dependent calibration, i.e., calibration of each timeslice. We use a Weighted Alternating Least Squares algorithm for multi-source self-calibration, as described in [5]. The algorithm solves for the best fitting calibration solutions in a Least-Squares sense and requires an initial sky model.

Transient detection is proposed via either analysis of each source’s light curve, generated by source extraction on every image timeslice, or via image level differencing. Both techniques require the minimizing of calibration errors to reduce the false detection rate of transients. One of the contributors to calibration errors are shifts in the observed positions of the sources in the sky-model due to ionospheric refraction, leading to model visibilities differing from observed visibilities, ultimately resulting in the non-convergence of the calibration process. We address this by estimating source positions from data using Weighted Subspace Fitting (WSF) [6], which is incorporated into every calibration cycle. The dynamic range of calibrated images is then improved by the subtraction of the visibility contribution of the brightest sources in the sky, along with their sidelobes.

The ASM just resolves the Sun. This precludes its modeling as a point source, while also preventing the suppression of the Solar flux by eliminating short baselines. During solar flares the Sun can be the dominant contributor of flux to visibilities, while morphing into a source containing multiple complicated components which change over the duration of the flare. This was discovered in test observations, in which calibration sometimes failed during significant solar activity. We have applied a sparse-reconstruction based algorithm to estimate a reasonable model of the flaring Sun in an automated manner. This was found to be effective, although being compute intensive. The approaches described above allowed for effective removal of the Sun and the bright radio sources dominating the observed visibilities. For algorithm validation while hardware is being developed, test data from all dipoles of six stations was acquired using existing LOFAR hardware and software. Fig. 2 shows images from data acquired on September 21, 2011, 12:39 hours UTC before and after the removal of the Sun

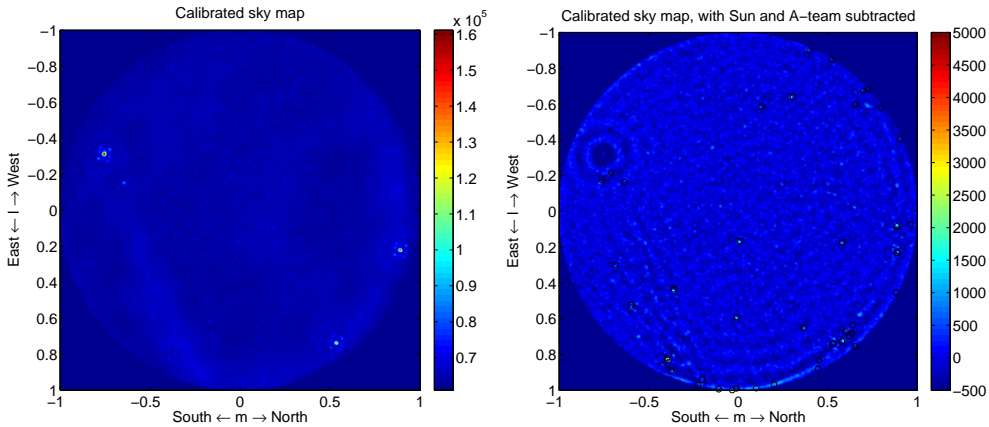


Figure 2. : (Left) Calibrated skymap with flaring Sun, CasA, CygA and Galactic plane visible. (Right) Map with the Sun and bright sources subtracted and the Galactic plane filtered out, making weaker sources visible. Over-plotted circles indicate the position of several 3C sources.

and bright sources. The noise in this image, generated using an time integration of 10 s and ~ 90 kHz bandwidth, indicates a dynamic range of $\sim 2200:1$.

4. Conclusion

The AARTFAAC ASM will be one of the first all-sky monitors at radio wavelengths. Its calibration is challenging because of the dynamic nature of the low frequency observations due to factors like an active ionosphere over an extremely large field of view, or Solar activity. We have shown that advanced algorithms can effectively address some factors at the cost of increased computing. The ASM's implementation is ongoing, with appropriate hardware procured and firmware in development. Appropriate calibration approaches are being developed based on experience gained via test observations.

References

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